IMPLICATION OF LANDSLIDE ACTIVITY FOR URBAN DRAINAGE

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ABSTRACT

A rainstorm on 20 December 1976 produced approximately 250-300 mm of rain in 12 hours in a small (12.7 km^2) steeply-sloping catchment, triggering 78 landslides with a total volume of 33,500 m^3. Seventy of the landslides provided debris directly to the drainage system producing a highly loaded torrent which caused severe flooding downstream. Peak discharges for 15 sub-catchments within the main valley were estimated using the Manning equation. Channels designed for storm runoff were inadequate for transporting the landslide debris.

INTRODUCTION

The accurate prediction of peak discharge has particular economic and human significance in urban areas where the property and safety of residents are at stake. During the catastrophic rainstorm of 20 December 1976, the urban part of the Stokes Valley, Lower Hutt, Wellington (Fig. 1), experienced severe flooding as a result of combined effects of high rainfall and the blocking of the drainage system by landslide debris.

The response of the Stokes Valley catchment has considerable significance for hydrological design throughout the Wellington region for a number of reasons. Although the rainstorm was of extremely low frequency (return period in excess of 100 years and possibly in excess of 500 years; Tomlinson, 1977) and beyond generally accepted design periods, landslide activity can occur with much greater frequency within the region (Eyles *et al.*, 1978). Eyles (1979) has shown that episodes of major landslip activity occur in Wellington City when daily rainfall exceeds the amount required to bring soil moisture to field capacity by 100 mm; an event which has a return period as low as 3.4 years.

The effect of landslide activity in Stokes Valley is likely to be paralleled throughout the Wellington region as urban development is moving into similar steep-sided, tributary valleys which are deeply incised in greywacke bedrock. This type of terrain is inherently more susceptible to landslide activity than that of valley floors and the larger, more gently sloping, catchments which were developed in earlier periods. Furthermore the modification of slopes for urban development enhances their susceptibility to mass movement (Eyles *et al.*, 1978). In Wellington this is of particular concern as much new subdivision is taking place in higher rainfall areas within the city.

THE STORM

The storm of 20 December 1976 produced extremely heavy rainfall in a southeast/northwest trending zone extending from Wellington City

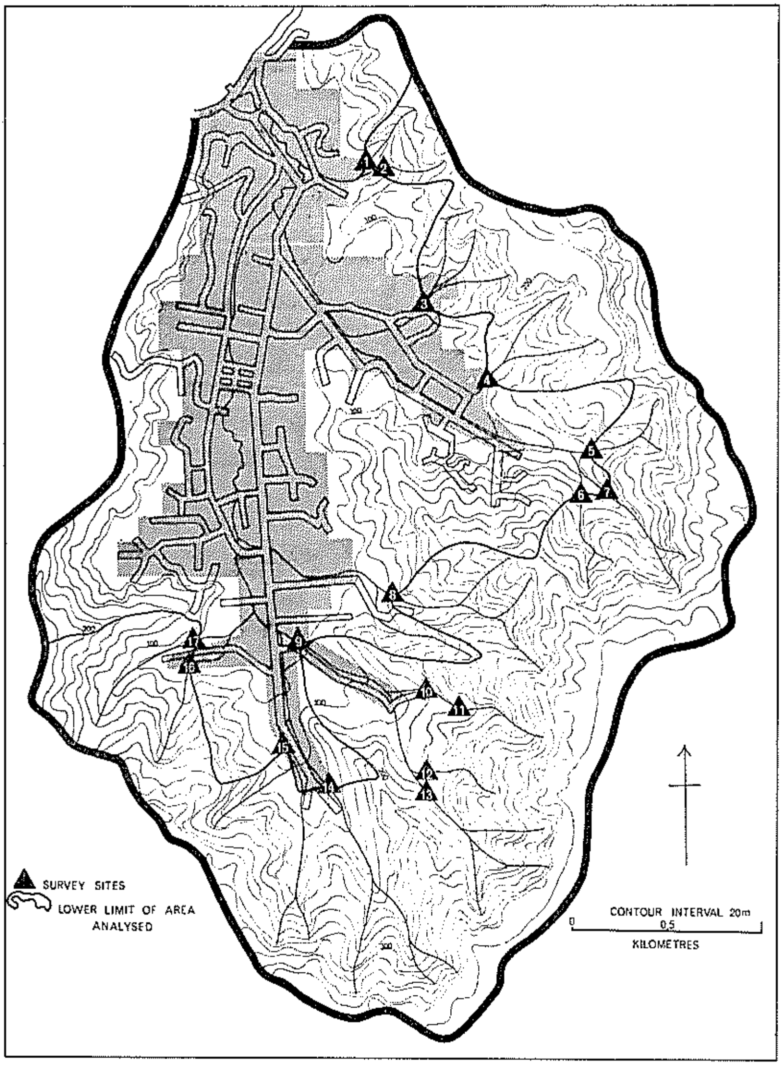

FIG. 1—Stokes Valley Catchment, Survey Sites.

to Upper Hutt (Tomlinson, 1977). A zone of convergent air flow, responsible for the heaviest rainfalls during the storm, extended across Stokes Valley and produced approximately 250-300 mm rainfall in 12 hours. The distribution of rainfall and runoff response during this period is illustrated by records from the nearest gauged catchment, at the DSIR Soil Bureau site, located in a basin adjoining Stokes Valley. Analysis of these records (Wellington Regional Water Board, 1976) indicates three separate storm peaks. The first with rainfall of 54 mm/h brought a runoff peak of 3 mm/h; the second with rainfall of 44 mm/h produced a 13 mm/h peak runoff; a final event with rainfall of 70 mm/h, and with allowance for some runoff from previous showers (8 mm/h), gave peak runoff of 50 mm/h. While these separate events lasted for between 30 minutes and one hour, the peak rainfall intensities were only maintained for up to 15 minutes.

LANDSLIDE ACTIVITY

Air photo interpretation and field survey of Stokes Valley located 78 landslides which occurred during the storm. All took place on scrub or forest covered slopes at angles in excess of 19 degrees and, significantly, 70 of them supplied debris directly into the drainage system.

A limiting equilibrium stability analysis (McConchie, 1977) has shown that the most likely mechanism of failure was complete saturation of the regolith as a result of the development of perched water tables during the storm. Water accumulated in the colluvial soils (Taita Hill Soils; Milne, 1971) as a result of the concentration of subsurface flow in drainage depressions and the inhibition of drainage by the underlying, relatively impermable bedrock surface.

Most landslides were located at the head of first order drainage lines and, as a result of the removal of regolith, the channel network has been extended and drainage density correspondingly increased. Based on morphological analyses of individual landslides within the field, the total amount of debris displaced by landslides is approximately 33,500 m^3. Most of this material appears to have been removed from the upper catchment, causing slight channel incision during transport, and deposited where the streams emerge onto the main valley floor or where flow is obstructed at other downstream locations. Thus the transport of landslide debris occurred predominantly within the channel system and combined with storm runoff to produce the total fluid discharge within the catchment.

The nature of the channel flow indicated the importance of the debris contribution to peak discharge. Residents reported pulses or waves in the steep sided gullies The stream ran at normal level, then dropped,' followed a few minutes later by a torrent of debris several metres above the normal level, a pattern described by Johnson (1970).

PEAK DISCHARGE

As Stokes Valley is an ungauged catchment, peak discharges within the channels (Table 1) were estimated using the Manning equation with channel cross-section area corresponding to the highest flood (rack) marks. Difficulties in identifying the flood channel, brought about by extensive over-bank flow and artificial channel modification at the time of the flood, prevented discharge assessment being made at the basin mouth or at sites on the floor of the main valley. Consequently discharge was calculated for 15 individual tributaries at 17 survey sites, located approximately where each tributary emerged onto the main valley floor (Fig 1). The specific location of each site represented a

TABLE 1—Velocities (m/s) and Peak Discharges (m^3/s) from Manning's Equation, Stokes Valley using four selected values of Manning's "n".

Sub Catchment No.	Sub Catchment Area (km^2)	Channel Cross-section Area (m^2)	Hydraulic Radius (m)	Slope (m/m)	Manning's Roughness Factor n							
					0.05		0.06		0.07		0.08	
					Velocity	Peak Discharge	Velocity	Peak Discharge	Velocity	Peak Discharge	Velocity	Peak Discharge
1	0.09	0.692	0.284	0.140	3.2	2.2	2.7	1.9	2.3	1.6	2.0	1.4
2	0.06	0.920	0.329	0.070	2.5	2.3	2.1	1.9	1.8	1.7	1.6	1.5
3	0.37	2.000	0.430	0.105	3.7	7.4	3.1	6.2	2.6	5.3	2.3	4.6
4	0.62	1.625	0.325	0.123	3.3	5.4	2.8	4.5	2.4	3.8	2.1	3.4
5	0.35	12.900	1.062	0.158	8.3	106.9	6.9	89.1	5.9	76.3	5.2	66.8
6	0.48	8.250	0.571	0.140	5.2	42.6	4.3	35.5	3.7	30.4	3.2	26.6
7	0.35	8.700	0.946	0.123	6.8	58.7	5.6	49.0	4.8	42.0	4.2	36.7
8	0.55	10.900	0.807	0.140	6.5	70.9	5.4	59.0	4.6	50.6	4.0	44.3
9	0.55	9.150	0.501	0.052	2.9	26.4	2.4	22.0	2.1	18.9	1.8	16.5
10		Culvert 1.25 m dia. n = 0.013						n = 0.013	Qp = 18.5			
11	0.29	12.980	0.998	0.249	10.0	129.5	8.3	107.9	7.1	92.5	6.2	80.9
12	0.14	4.030	6.611	0.105	4.7	18.8	3.9	15.7	3.3	13.4	2.9	11.8
13	0.58	6.980	0.821	0.123	6.1	42.9	5.1	35.8	4.4	30.6	3.8	26.8
14	0.79	0.250	0.167	0.087				n = 0.013	Qp = 1.5			
15	0.88	2.250	0.459	0.087	3.5	7.9	2.9	6.6	2.5	5.7	2.2	5.0
16	0.24	2.850	0.475	0.070	3.2	9.2	2.7	7.6	2.3	6.6	2.0	5.7
17	0.47	3.480	0.497	0.087	3.7	12.9	3.1	10.8	2.7	9.2	2.3	8.1

position immediately upstream of where the channel gradient flattened abruptly and which also marked the point where channel infilling had taken place as the flood subsided. Discharge values determined in this way represent the flow of the total fluid system, debris and water, within the channel.

The use of Manning's equation and specifically selection of the required roughness factor (n) is contentious especially when dealing with a fluid system of a highly viscous nature. Of the three factors in the equation two have been measured directly in the field (hydraulic radius and slope) and the third (Manning's "n") requires a degree of subjective assessment. The selection of a suitable value for "n" (Table 1) could normally be checked by comparing the resultant calculated velocity against measured velocities, but in this case there were none. A check can be made by comparing calculated velocities against those measured for similar types of fluid debris movements recorded in the literature. Varnes (1958) for example classifies debris avalanches as having rates of movement in excess of 3 m/s. Sharp and Nobles (1953) writing of flows of "slimy gray cement-like" mud with viscosities of 10^3 poise mention surge front velocities of up to 5 m/s, and averaging 3 m/s, on slopes of less than ten degrees. Curry (1966) measured velocities of up to 16.3 m/s, on slopes of up to 41 degrees, of debris flows with an average water content of nine per cent by weight and viscosities of 10^4 poises.

Within Stokes Valley the majority of valley side slopes are greater than 30 degrees (McConchie, 1977), suggesting that similar velocities were possible for debris flows. Four values of "n" were used resulting in a range of velocities and peak discharges (Table 1). The values of "n" within the range chosen do not greatly affect the calculated velocities. With such high concentrations of solids within the fluid system it might be expected that the value of "n" would be higher than that indicated from channel characteristics alone. However, debris flows have been shown to exhibit laminar movement (Johnson, 1970) which would tend to offset the effect of channel roughness. In addition, the material involved contains kaolin derived from the weathering of local greywacke and this also acts to dampen turbulence (Johnson, 1970). A value of 0.06 gives results that compare reasonably well with those obtained in other areas.

In tributary catchments homogeneous with respect to bedrock, soil cover, vegetation, drainage density and slope, it could be expected that if runoff was a dominant component of the material flowing in the channel, and if rainfall was uniform in space, peak discharge would be closely related to catchment area. The inability of area to explain the variation in peak discharge must result from other factors such as the areal distribution of storm rainfall, the contribution of landslide debris to channel flow, or inaccurate estimates of peak discharge.

It is a moot point as to whether the peak flows which occupied the channels during the storm represent a hydrological or mass movement process. What is beyond contention, however, was the inability of the urban drainage systems to cope with the flows. Although the culvert (Table 1) had a theoretical capacity of 18.4 m^3/s and could probably have coped with runoff alone, it was totally inadequate for the peak discharge of fluid material which actually occurred.

IMPLICATIONS FOR PLANNING

It is clear from the results of this survey that landslide debris must be considered in drainage design in areas of unstable terrain. Although the event described has a return period at least in excess of 100 years, Tomlinson (1977) states: ". . . storms of the intensity of that of 20 December 1976 will occur in different parts of the region at much shorter intervals than the return period mentioned above." In addition, urbanization in Wellington is taking place increasingly in small, steep tributary catchments and as a result of "cut and fill" operations the total area of slopes susceptible to mass movements is increasing.

Landslide activity is not uncommon in the Wellington region (Eyles, 1979) and throughout the country episodes of slipping occur every year. In comparison with other recently recorded episodes (Table 2) the Stokes Valley event did not involve an unusually high volume of landslide debris.

In areas that show evidence of previous landslide activity or which are potentially unstable, it is useful to be able to estimate the likelihood

TABLE 2—Slope Denudation Rates from Landslide Displacement.

Denudation Rate (mm/year)	Location	Vegetation Cover	Geology	Source
0.03	Stokes Valley	forest	weathered greywacke	McConchie, 1977
0.1	North Westland[2]	forest	gravels and sandstone	O'Loughlin and Pearce, 1976
0.25-0.5	South Auckland[1]	forest	weathered greywacke	Selby, 1976
1.0	South Auckland[1]	pasture	weathered greywacke	Selby, 1976
1.1	North Westland[2]	clear felled (young pines)	Waimaugan gravels	O'Loughlin and Pearce, 1976
1.4	North Westland[2]	clear felled (young pines)	Old Man gravels	O'Loughlin and Pearce, 1976
1.5-2.3	Hawkes Bay[1]	pasture	loess and ash on siltstone	Eyles, 1971
2.8	South Eastern[3] Ruahine Ra.	forest	greywacke	Mosley, 1977
4.0	North Westland[2]	clear felled .young pines)	standstone	O'Loughlin and Pearce, 1976

[1] Calculated on the basis of the recurrence interval of the landslide-producing event.

[2] Volume of landsliding observed 1973-75.

[3] Change in the volume of landslide scars between 1946 and 1974.

(Data provided by M. J. Crozier, Victoria University of Wellington, pers. comm.).

of landslide activity occurring during storms. One approach is to determine minimum triggering rainfalls for landslide activity for the type of terrain under consideration by methods similar to those outlined in Eyles *et al.* (1978) and Eyles (1979). The return periods of these threshold rainfalls can be compared to the selected design period for channel structure. If the return period of the triggering rainfall is less than that of the design discharge, then the volume of debris contributed to peak discharge needs to be estimated. With this information, channel capacity and strategically placed debris traps can be designed rationally.

General assessment of potential debris contribution needs to be based on a number of factors including: stability of slopes, relationship of landslide volume to rainfall amounts, the location of unstable ground with respect to the drainage system, the proportion of landslide debris entering the drainage system, and the relationship between the time of landslide occurrence and peaks in storm runoff.

CONCLUSIONS

The geomorphic and hydrological responses to an extreme event cannot be considered separately in areas susceptible to landslide activity. In drainage channel design, landslide debris must be considered when the design storm rainfall is greater than the landslide triggering rainfall.

The frequency of storm-triggered landslides within the Wellington region suggests that future planning would benefit from an understanding of the relationship between slope and fluvial processes during storms.

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